Ocean Acoustics Turbulence Study

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LONG-TERM GOALS

Develop tools and techniques to remotely quantify the three-dimensional spectrum of scalar and vector ocean turbulence using high frequency broadband multi-static acoustic scatter from medium variability.

OBJECTIVES

Validate the application of far-field weak scattering theory to thermal-saline turbulent jets and compare the acoustic spectral estimates with the universal gradient spectral model for the inertial and Batchelor sub-ranges.

APPROACH

Following the successful application of far-field weak scattering theory and broadband multi-static scattering to thermal plumes where the dominant scattering mechanism is a thermally induced change in sound speed, a similar approach is used to examine the scattering from saline and thermal-saline turbulent jets.[1] Scattering from fluctuations in salinity arise from both a change in the sound speed and density of the fluid. As a consequence, the scattering from salinity fluctuations has both a monopole and dipole scattering terms and thus an explicit angular dependence in the complex acoustic scatter. Common Bragg wave number comparisons for overlapping spectral components are utilized to validate the explicit angular dependence for scattering from salinity variability alone. This is similar to previous work for scattering from thermal plumes where this approach at least indirectly verifies the theoretical description of the scattering process. In an attempt to independently "ground truth" the observed acoustic scatter, spectral comparisons are made between the results from the acoustic scatter and a universal gradient spectral model.[2] Inertial and Batchelor sub-ranges are both used to describe the wide bandwidth of information obtained using the broadband multi-static approach. Input model parameters are estimated using flow rates, mean gradient differences, and jet diameters.

Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

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1. REPORT DATE **30 SEP 2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**
4. TITLE AND SUBTITLE **Ocean Acoustics Turbulence Study**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Coastal Systems Station,,6703 West Highway 98,,Panama City,,FL,32407**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT **Develop tools and techniques to remotely quantify the three-dimensional spectrum of scalar and vector ocean turbulence using high frequency broadband multi-static acoustic scatter from medium variability.**		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

WORK COMPLETED

High frequency broadband multi-static acoustic scatter measurements are made from saline, thermal and saline-thermal turbulent jets. The far-field weak scattering theory results in the complex acoustic scatter being described by

$$p_s(\omega) = \frac{k^2 p_i(\omega)}{4\pi r} \int Q(\boldsymbol{x}) exp(-i\boldsymbol{K} \cdot \boldsymbol{x}) d\boldsymbol{x}$$

where $p_{i,s}$ are the incident and scattered pressure fields, respectively, k is the acoustic wave number, r is the volume to receiver range, $\boldsymbol{K}$ is the Bragg wave vector, and Q is the scattering source term given by

$$Q(\boldsymbol{x}) = [2\frac{1}{c}\frac{\partial c}{\partial T} + \frac{1}{\rho}\frac{\partial \rho}{\partial T}(1-cos\theta)]T(\boldsymbol{x}) + [2\frac{1}{c}\frac{\partial c}{\partial S} + \frac{1}{\rho}\frac{\partial \rho}{\partial S}(1-cos\theta)]S(\boldsymbol{x})$$

where c is the sound speed, ρ is the density, and T and S are temperature and salinity differences from ambient, respectively.

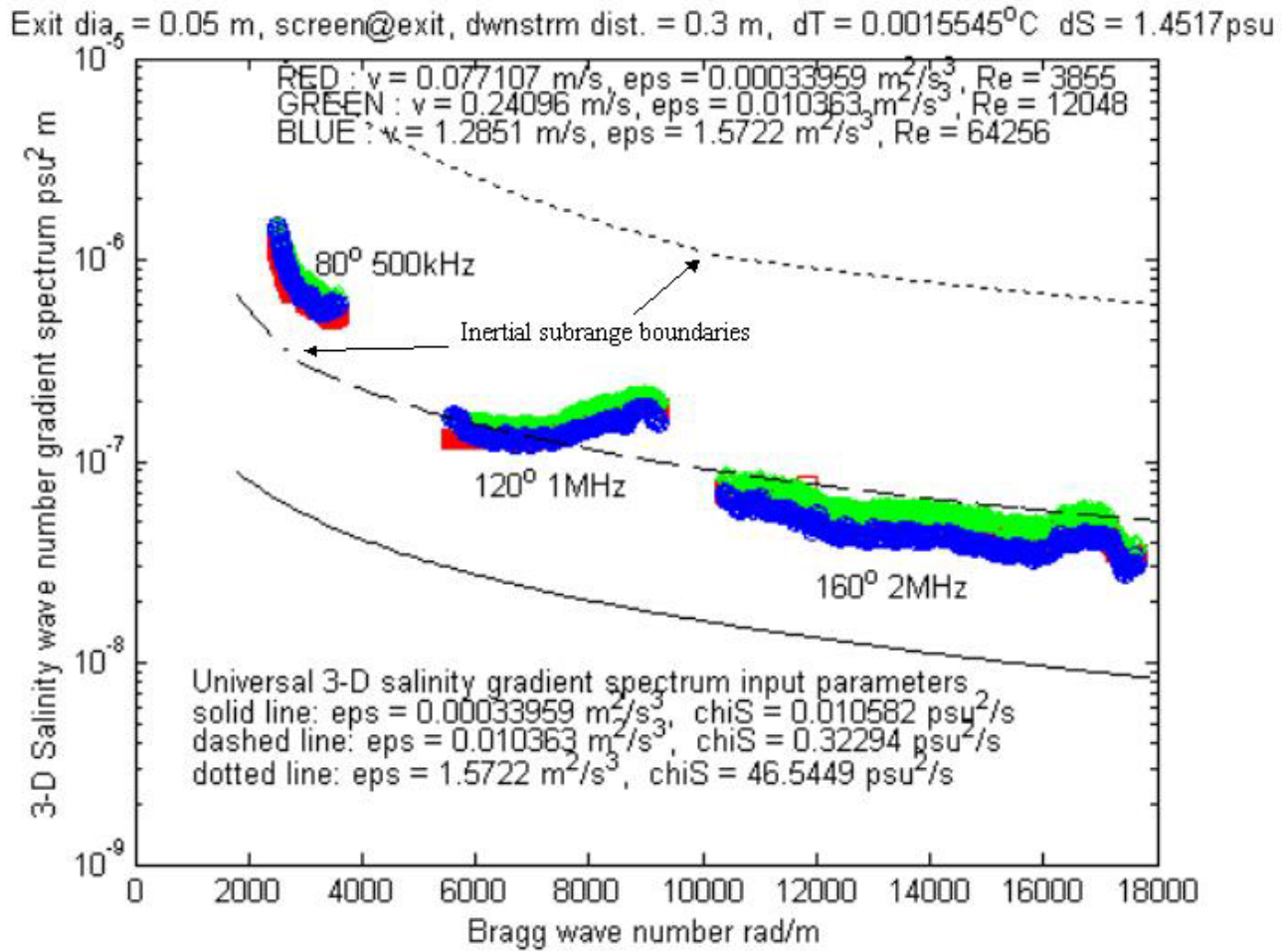The acoustic spectral estimate is given by

$$\Phi(K) = (2\pi)^3 (4\pi r)^2 \, | \, p_s \, / \, p_i \, |^2 \, /(k^4 V)$$

where V is the volume defined by the source-receive beam patterns, and estimated by the intersection of circular cones at the appropriate scattering angle using 10 dB down points.

Three different exit velocities are used to provide a range in the expected spectral magnitude and form. The one-dimensional universal gradient spectral model used is found in Dillon and Caldwell.[2] The two input parameters are the dissipation rates of the turbulent kinetic energy ε, estimated using the exit velocity and jet diameter, and the thermal/saline variances χ, estimated by using a mixing efficiency equation.

Figures 1 and 2 represent the acoustic and model results for turbulent saline and thermal jets, respectively. Since the diffusivity of salt of is two orders of magnitude smaller than for temperature, for a given range of available acoustic frequencies, scattering from salinity fluctuations will yield results at smaller non-dimensional wave numbers than for scattering from temperature. This is clearly seen in the differences in the model predictions between Fig. 1 where there exists an inertial sub-range, whereas in Fig. 2, two of the cases contain the Kolmogorov wave number, or regions near the maximum of the one-dimensional gradient spectrum in the Batchelor subrange.

One interesting feature in Fig.1 is that the acoustic results are independent of the exit velocity, something that is not predicted by the model for the parameters used. Note also the difference between smoothly varying model results verses the acoustic results that has noticeable structure in the spectrum.

Exit dia$_s$ = 0.05 m, screen@exit, dwnstrm dist. = 0.3 m, dT = 0.0015545°C dS = 1.4517psu

RED : v = 0.077107 m/s, eps = 0.00033959 m²/s³, Re = 3855
GREEN : v = 0.24096 m/s, eps = 0.010363 m²/s³, Re = 12048
BLUE : v = 1.2851 m/s, eps = 1.5722 m²/s³, Re = 64256

80° 500kHz

Inertial subrange boundaries

120° 1MHz

160° 2MHz

Universal 3-D salinity gradient spectrum input parameters
solid line: eps = 0.00033959 m²/s³, chiS = 0.010582 psu²/s
dashed line: eps = 0.010363 m²/s³, chiS = 0.32294 psu²/s
dotted line: eps = 1.5722 m²/s³, chiS = 46.5449 psu²/s

3-D Salinity wave number gradient spectrum psu² m

Bragg wave number rad/m

Figure 1. The three-dimensional salinity wave number gradient spectrum as a function of Bragg wave number for three different jet exit velocities; red, green, and blue represent the acoustic data for exit velocities of 0.08, 0.24, and 1.29 m/s, respectively, corresponding to dissipation rates of the turbulent kinetic energy of 3e-4, 1e-2, and 1.6 m²/s³, respectively, and dissipation rates of the saline variance of 1e-2, 3e-1, and 47 psu²/s, respectively. The solid, dashed, and dotted lines are the predicted model results for the corresponding three cases examined. The acoustic scatter in the 2,000 to 4,000 rad/m band are collected at a scattering angle of 80 degrees and center frequency of 500 kHz; for the 5,000 to 9,000 rad/m band, the scattering angle is 120 degrees and center frequency of 1 MHZ, and for the 10,000 to 18,000 rad/m band the scattering angle is 160 degrees and center frequency of 2 MHz.

In Fig. 2 are the spectral results for scattering from turbulent jets where the temperature difference from ambient dominates salinity differences. As noted above, the results from the thermal fluctuations include portions containing the local maximum of the non-dimensional spectrum near the Kolmogorov wave number.   Note that at the lowest Bragg wave numbers measured, that the acoustic results do not separate as the model predicts for the three different exit velocities used. However at higher wave numbers, the acoustic results do depend upon the exit velocities in the same order as predicted.
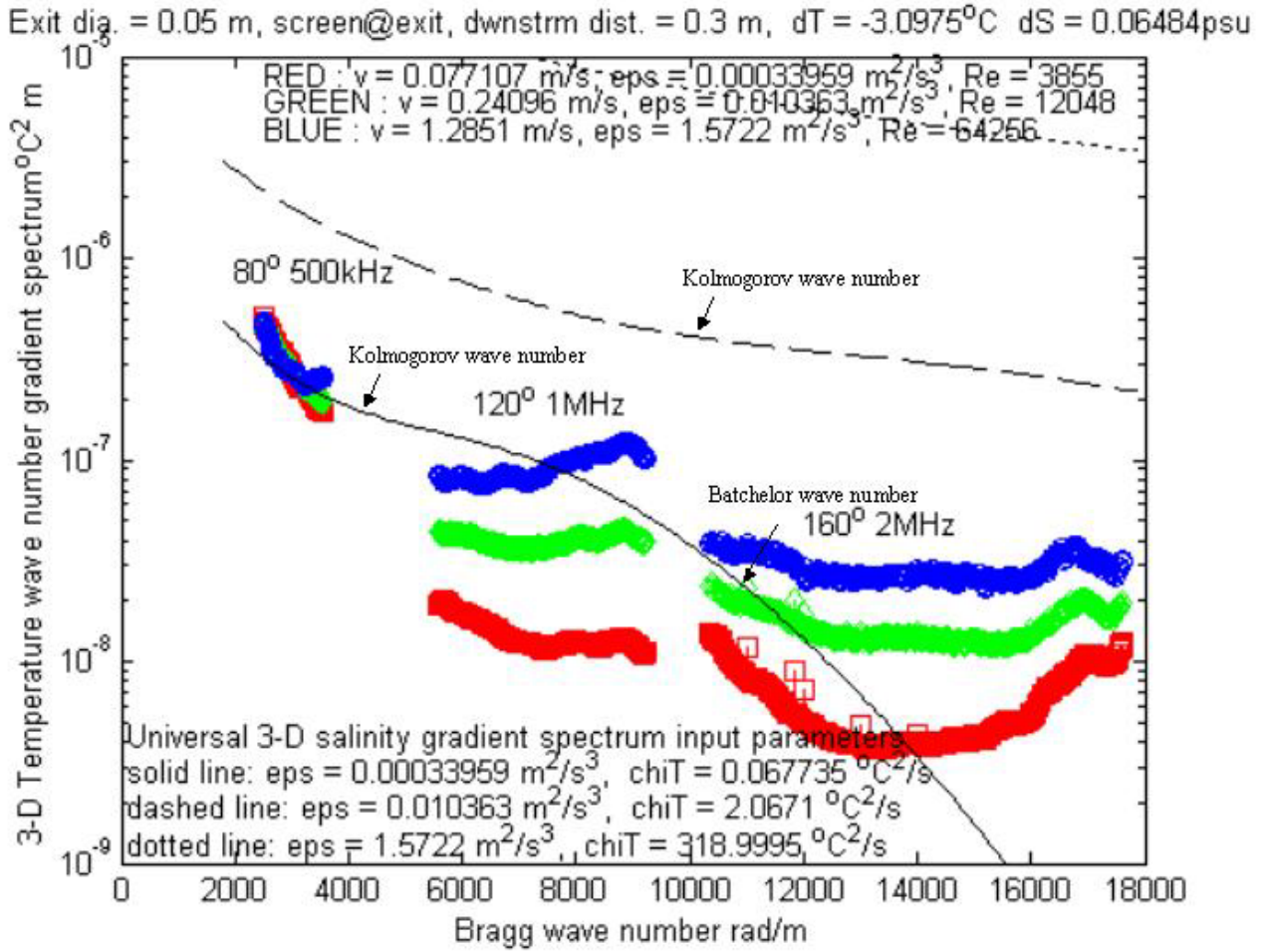
Figure 2. The three-dimensional temperature wave number gradient spectrum as a function of Bragg wave number for three different jet exit velocities; red, green, and blue represent the acoustic data for exit velocities of 0.08, 0.24, and 1.29 m/s, respectively, corresponding to dissipation rates of the turbulent kinetic energy of 3e-4, 1e-2, and 1.6 m²/s³, respectively, and dissipation rates of the thermal variances of 7e-2, 2.1, and 319 °C²/s, respectively. The solid, dashed, and dotted lines are the predicted model results for the corresponding three cases examined. The acoustic scatter in the 2,000 to 4,000 rad/m band are collected at a scattering angle of 80 degrees and center frequency of 500 kHz; for the 5,000 to 9,000 rad/m band, the scattering angle is 120 degrees and center frequency of 1 MHZ, and for the 10,000 to 18,000 rad/m band the scattering angle is 160 degrees and center frequency of 2 MHz.

In Fig. 3 are results for a common Bragg arrangement for scattering from a turbulent jet containing saline-thermal variability. In this case, the model predictions show an increase in the spectral magnitude as the scattering angle increases. However, the acoustics for the 1.5 MHz center frequency data appears as an outlier that does not follow the predicted trend.

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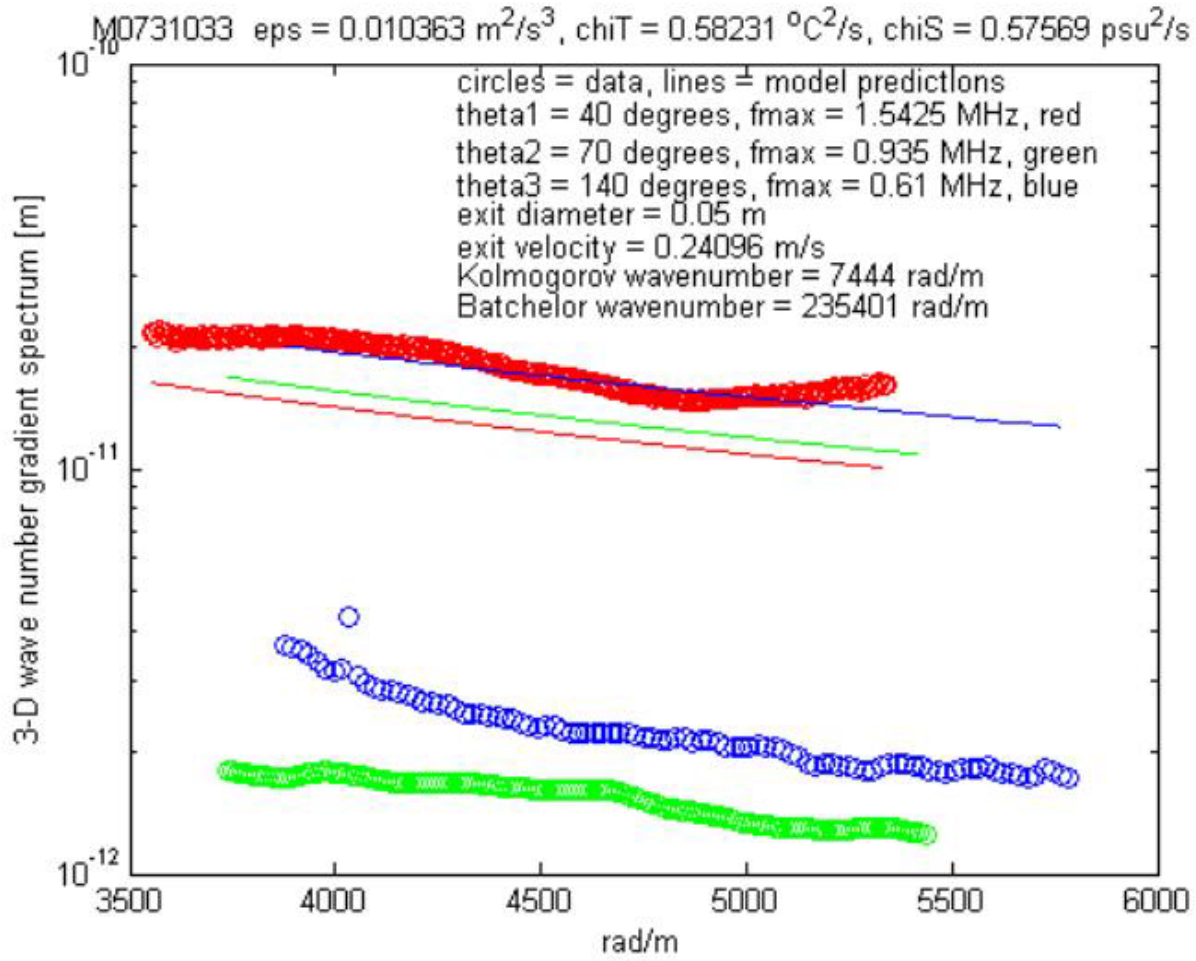
Figure 3. *The three-dimensional wave number gradient spectrum of a turbulent thermal-saline jet at common Bragg wave numbers with exit velocity 0.24 m/s, corresponding to a dissipation rate of the turbulent kinetic energy of 1e-2 m^2/s^3 and dissipation rates of the thermal and saline variances of 6e-1 $^oC^2/s$ and psu^2/s, respectively. The red, green, and blue represent the acoustic data for 40, 70, and 140 degrees scattering angles, respectively; at center frequencies of 1.5 MHz, 0.9 MHz, and 0.6 MHz, respectively. The solid red, green, and blue lines are the predicted model results corresponding to the 40, 70, and 140 degrees scattering angles measured, respectively.*

RESULTS

Outstanding issues are the apparent discrepancy between the expected dependence upon the exit velocity, or the dissipation rates in the acoustic spectral estimates; the overall offset between the model predictions and the acoustic results; and the anomalous result in Fig. 3 for the 1.5 MHz data. These have led to preliminary work that indicates that more accurately describing the scattering volume may be important. Instead of using a volume estimated from the intersection of right circular cones that incorporate the expected frequency dependence at the 10 dB down points for a baffled cylinder, it appears that a more complex "weighted volume" that must be determined numerically is necessary. Also, the structure in the acoustic results suggests the fluctuations generated using the jet may not be fully developed turbulence.

IMPACT/APPLICATIONS

Broadband multi-static acoustic scatter from medium variability may potentially allow for remote and rapid environmental characterization that assist in predicting sonar performance and limitations in harsh locations.

RELATED PROJECTS

None.

REFERENCES

[1]J. Oeschger, and L. Goodman , "Acoustic scattering from a thermally driven buoyant plume revisited", J. Acoust. Soc. Am. **113**, 1353-1367, (2003)

[2]T. Dillon and D. Caldwell, "The Batchelor spectrum and dissipation in the upper ocean", J. Geophys. Res. **85**, 1910-1916 (1980)

PUBLICATIONS

"Acoustic scattering from a thermally driven buoyant plume revisited" John Oeschger and Louis Goodman, J. Acoust. Soc. Am. 113, 1353-1367, (2003) [published, refereed]